Report 4554

Mechanical Properties and Seawater Behavior of Nitronic 50 (22Cr-13Ni-5Mn) Plate

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

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MECHANICAL PROPERTIES AND SEAWATER BEHAVIOR OF NITRONIC 50 (22Cr-13Ni-5Mn) PLATE

by

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MATERIALS DEPARTMENT

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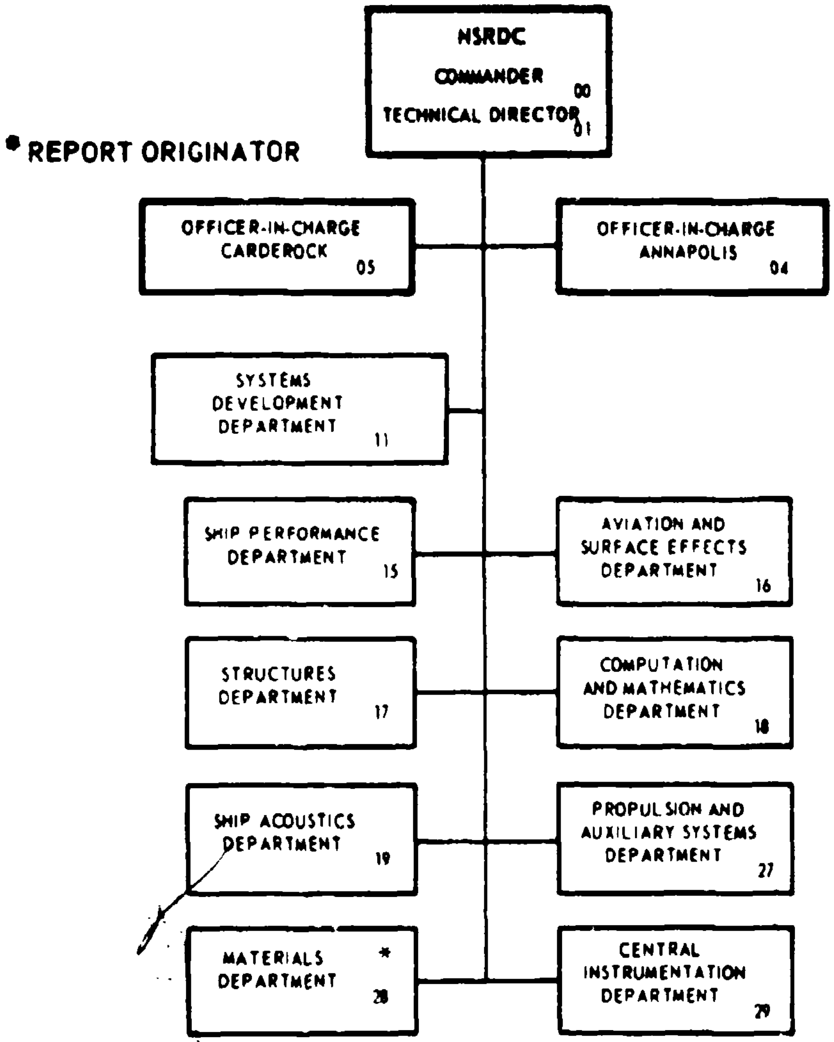

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The mechanical properties and seawater behavior of Nitronic 50 (22Cr-13Ni-5Mn) have been investigated. One-inch base plate and gas metal-arc weldments were used for this study. Good elongation and toughness properties were obtained. The yield strength of the weld metal was overmatching (80 versus 63 thousand pounds per square inch). The alloy demonstrated satisfactory stress-corrosion resistance. Base metal, high- and low-cycle fatigue

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performance was excellent, but gas metal-arc weldments performed poorly because of weld porosity. The corrosion behavior of Nitronic 50 is not adversely affected when coupled to common naval alloys. In most cases, it behaves cathodically and accelerates the corrosion of these alloys. While Nitronic 50 does not display general pitting corrosion, it does evidence crevice corrosion, but to a much lesser degree than most common stainless steels.

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ADMINISTRATIVE INFORMATION

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LIST OF ABBREVIATIONS

AB	- alternating bend specimen
ASTM	- American Society for Testing Materials
avg	- average
Bal	- balance
cfh	- cubic feet per hour
c/m	- cycles per minute
CVN	- Charpy V-notch
DT	- dynamic tear
FLLCL	- Francis L. LaQue Corrosion Laboratory
ft-lb	- foot-pound
ft-sec	- feet per second
GMA	- gas metal-arc
GMAW	- gas metal-arc welding
GTA	- gas tungsten-arc
in/in/min	- inch per inch per minute
in^2	- square inches
in-lb	- inch-pound
ipm	- inches per minute
kJ/in	- kilojoules per inch
ksi	- thousand pounds per square inch
ma	- milliamperes
max	- maximum
misc	- miscellaneous
mpy	- mils per year
mv	- millivolts
No.	- number
Oe	- oersteds
ppt	- parts per thousand
psi	- pounds per square inch
RC	- rotating cantilever specimen
SCC	- stress-corrosion cracking
SMA	- Shielded metal-arc
SRW	- Severn River water
SW	- seawater
temp	- temperature
wt	- weight
YS	- yield strength

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INTRODUCTION

OBJECTIVE

This study is aimed at assessing the suitability of a nonmagnetic ferrous alloy for use in naval structures.

Specifically, this investigation is concerned with determining the strength, toughness, fatigue, and corrosion behavior of 1-inch Nitronic 50* (22Cr-13Ni-5Mn) base plate and gas metal-arc weldments. The seawater studies include evaluation of crevice, galvanic, fatigue and stress-corrosion-cracking behavior. For comparison purposes, a large number of stainless alloys (31) were screened by an accelerated crevice-corrosion test.

BACKGROUND

New nonmagnetic nitrogen-strengthened alloys (up to 0.4 weight % N_2) have been developed that have higher strength and better seawater-corrosion resistance than standard 300 series stainless steels. One commercial alloy that shows promise for structural applications is Nitronic 50 (22Cr-13Ni-5Mn). Therefore, an investigation was conducted to determine its suitability for naval use.

Evaluations of the weldability (SMA, GMA AND GTA)** of Nitronic 50 plate have been conducted concurrently at the Center and are reported separately.

MATERIAL

BASE PLATE

One-inch-thick Nitronic 50 plate was produced from a 14,800-pound, 17-inch-thick ingot that was reduced to a 7-inch-thick slab at 2175° F. The slab was then rolled to 1 inch at 2275° F and subsequently annealed at 2050° F for 1 hour and water quenched. The microstructures of longitudinal and transverse sections appear in figure 1. The chemical composition of this material is given in table 1.

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*Armco Steel designation.
**A list of abbreviations used appears on page i.

TABLE 1
CHEMICAL COMPOSITION
OF NITRONIC 50 BASE PLATE, WEIGHT PERCENT

Material Code	EXV
Heat No.	302556-2A
Composition	
Fe	Bal
C	0.048
Cr	21.55
Ni	11.97
Mn	4.49
Mo	2.17
N	0.20
Cb	0.21
V	0.15
P	0.015
S	0.006
Si	0.33

The current price per pound of Nitronic 50 is $1.75, as compared to $1.00-$1.25 for standard 300 series stainless and $8-$10 for titanium alloy plate.

WELDMENTS

Gas metal-arc weldments for high-cycle fatigue, dynamic-tear, and stress-corrosion tests were prepared by the Philadelphia Naval Shipyard at the direction of the Center's Ferrous Welding Branch of the Fabrication Technology Division.

Modified columbium-free electrodes (0.062-inch diameter) were purchased from the Armco Steel Corporation. Compositions of the modified weld wire and resultant weld metal are shown in table 2.

TABLE 2
CHEMICAL COMPOSITION OF WELDING WIRE
AND GMA WELD, WEIGHT PERCENT

Element	Material	
	Filler Wire	GMA Weld
C	0.030	0.040
Cr	21.21	21.05
Ni	10.48	11.00
Mn	6.22	5.65
Mo	1.83	2.00
N	0.23	0.15
Cb	0.0	0.027
V	0.27	0.19
P	0.011	0.016
S	0.014	0.010
Si	0.44	0.30
Fe	Bal	Bal

Two plates, 1 x 13 x 13 inches, were welded by the automated GMAW spray process. Both were welded in the flat position using a 45° single V-bevel joint with a 1/4-inch-thick backing strip of matching composition. Details of welding parameters are given below:

Electrode diameter	- 0.062 inch
Current	- 300 amperes
Voltage	- 28 volts
Travel speed	- 15 ipm
Heat input	- 33 kJ/in
Preheat temperature	- 60° F (minimum)
Interpass temperature	- 250° F (maximum)
Shielding gas mixture (flow rate)	- Argon (40 cfh)

Radiographic examination rated the GMAW-spray welds as class II quality, based on HY-80 weld metal acceptance standards. Defects were generally porosity-type voids distributed throughout the weld metal. The microstructure of a sectioned weldment is shown in the montage of figure 2 (porosity is indicated by the arrow).

METHOD OF INVESTIGATION

TENSILE PROPERTIES

Tensile specimens of 0.505-inch diameter by 4.75 inches long were tested in accordance with standard ASTM procedures. The strain rate was 0.002 in./in./min until yielding occurred. Specimen blanks were taken from random plate locations both longitudinal and transverse to the principal rolling direction.

IMPACT AND DYNAMIC-TEAR PROPERTIES

Standard Charpy V-notch impact tests were run on base metal and weldments in accordance with ASTM procedures. Specimens were taken from the transverse plate direction and notched normal to the original plate surface. Impact tests were run at room temperature, 32° F and -82° F.

Dynamic-tear tests were performed on base metal and weldments at 32° F. Subsize, 5/8-inch-thick DT specimens (figure 3) were taken transverse to the plate rolling direction and notched normal to the original plate surface. Welded samples were notched in the weld as in the case of the CVN specimens.

STRESS CORROSION

The notched-bar stress-corrosion test[1] was used to determine the SCC susceptibility of base metal and weldments in seawater. These tests were conducted at the International Nickel

[1]Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

Company, Francis L. LaQue Corrosion Laboratory, Wrightsville Beach, North Carolina. Specimens were taken transverse to the plate rolling direction and notched normal to the original plate surface. Welded samples were notched in the center of the weld. Seawater was contained within the notched region of each specimen by means of a plastic reservoir.

The cantilever SCC specimen is shown in figure 4. The 0.004-inch radius notch was sharpened by fatigue cracking, resulting in a 50% total notch depth. The fatigue crack (approximately 0.050-inch long) was developed under high-cycle flexural conditions by using a Man Lab fatigue cracking machine. The actual crack depth was determined after failure by examining the fracture surface under a microscope at low magnification and taking the average of three readings along the crack front.

Initial stress intensities were calculated according to the following relationship developed by Kies.[1]

$$K_{I_i} = \frac{4.12\, M\left(\frac{1}{\alpha^3} - \alpha^3\right)^{1/2}}{BW^{3/2}},$$

where,

M = bending moment, in-lb

B = thickness, in.

W = depth, in.

a = crack length, in.

$\alpha = 1-a/w$.

The maximum stress intensity was obtained by incrementally loading one specimen in air ($K_{I_{air}}$; time to failure $\approx$ 0). Threshold curves for 1300 hours were obtained by running subsequent tests in seawater at stress intensity values less than $K_{I_{air}}$. Since the yield strength for the weld metal was different from that of base metal, normalized stress intensity data (K_{I_i}/YS) was also plotted.

FATIGUE

Two types of flexural fatigue specimens were used in this investigation. High-cycle fatigue tests were performed with both smooth and notched rotating cantilever beam specimens, as shown in figure 5. These were constant stress amplitude tests at a cyclic frequency of 1450 c/m. The smooth specimens were circumferentially and longitudinally polished to a metallographic finish.

Low-cycle fatigue tests were performed with equipment described previously.[2] Flat flexural-type specimens (smooth and notched) having the dimensions shown in figure 6 were used. The short end of the specimen was held stationary, while the long end was flexed between mechanical stops by a hydraulic piston. Longitudinal strain was measured by strain gages. The cycle rate ranged from 0.4 to 5.0 c/m for the air tests and from 0.25 to 1.0 c/m for those in salt water.

All of the fatigue tests were of the completely reversed type (fatigue ratio R = -1). In the corrosion fatigue tests, Severn River water, a brackish estuary water containing 1/6 to 1/3 the salt content of natural seawater, depending upon season and tide, was used.

Failure in the high-cycle, rotating cantilever-beam tests consisted of complete fracture. Failure in the low-cycle specimen tests was defined as the formation of one or more surface cracks 1/8 to 3/16 inch in length. The theoretical stress concentration factors for the high- and low-cycle notched fatigue specimens are 3 and 2.4, respectively.

There is general agreement that low- and intermediate-cycle fatigue life is dependent on total strain range.[2] Accordingly, the total strain range for each low-cycle fatigue specimen was determined, after conditions became stabilized, from a strain gage attached to the test section. The total strain range was then converted to a reversed strain-based stress (pseudoelastic stress) by the following relationship.

$$S_\varepsilon = \frac{E}{2}(\Delta\varepsilon_T) \quad ,$$

where

S_ε = reversed strain-based stress, psi

E = modulus of elasticity, psi

$\Delta\varepsilon_T$ = total strain range.

In the case of the high-cycle fatigue tests, the maximum nominal reversed stress was calculated from the applied deadweight load and the dimensions of the specimen, disregarding notch effects. The nominal stress and strain-based stress are assumed to be the same in the high-cycle tests, since the behavior of the specimen is essentially elastic.

GALVANIC CORROSION

Fifteen galvanic couples were exposed for 30 days in flowing (3 ft/sec) seawater at FLLCL. Each specimen (1/4 x 2 7/8 x 1 3/16 inches) was paired with a Nitronic 50 sample of the same

size in the polarization cell. The alloys coupled to Nitronic 50 are listed in the section entitled "Results and Discussion." Specimens were coated on the sides, ends, and back. A "window" configuration exposed one face of each alloy to the seawater (exposed area = 2.875 in^2). Electrical continuity between specimens was maintained by means of a wire attached to a screw contact at the rear of each specimen. Measurements of the mixed potential and current flow for each couple were recorded daily. Corrosion rates were determined at the conclusion of the test period.

CREVICE CORROSION

These tests were conducted as a screening study in order to characterize the crevice-corrosion behavior of a large number of stainless steel alloys. Thirty-one different stainless steel panels (mostly 4 x 6 inch) were exposed for 30 days in flowing seawater, 2 ft/sec, at FLLCL.

A Delrin* multiple-crevice assembly[3] was attached to each panel and provided 20 crevices per side. This accelerated test produces a bold (exposed)/shielded area ratio of about 300/1 (150/1 for subsize specimens). The materials were obtained in the as-rolled condition and sandblasted prior to test. After the 30-day immersion, data on weight loss, the number of corroding crevices, and the maximum depth of attack were tabulated for each panel.

MAGNETIC PERMEABILITY

The magnetic permeability and ferrite determinations of weldments were performed by Armco Steel Corporation in cooperation with the Ferrous Welding Branch of this laboratory. A 3-inch by 0.4-inch-diameter specimen was prepared in accordance with method 2 of ASTM 342-64 (1970). Testing was conducted at field strengths of 50, 100 and 200 oersteds. The percent ferrite was determined by the use of a Magne-gage following the procedure outlined by DeLong.[4]

RESULTS AND DISCUSSION

TENSILE AND IMPACT

Table 3 presents the tensile and impact data obtained in this investigation. Also included are the minimum acceptable properties specified by Armco Steel. The yield strength obtained for the base metal (62 ksi) is 7 ksi greater than the minimum value (55 ksi). Almost no directionality in properties was found.

*E. I. du Pont designation.

TABLE 3

TENSILE AND IMPACT PROPERTIES FOR NITRONIC 50 PLATE

	Yield Strength (0.2% Offset) ksi	Tensile Properties[1] Ultimate Tensile Strength ksi	Elongation %	Reduction in Area %	CVN ft-lb +75° F	CVN ft-lb +32° F	CVN ft-lb -80° F	Dynamic Tear ft-lb (+32° F)
		Minimum Acceptable Properties, Base Metal						
Longitudinal	55	100	40	60	-	-	-	-
		Base Metal						
Transverse	63	120	43	85	92/97	72/78	60/68	700/730
Longitudinal	62	120	45	62	82/94	76/86	74/77	-
		GMAW Weldments						
Transverse	73	112	22	31	66[2]/95	75/76	51[3]/55[3]	700/840
All Weld Metal	80	105	37	45	-	-	-	-

(1) Data represents average of several results.
(2) Extensive porosity; point not plotted on figure.
(3) Test temperature, -100° F.

Weld metal yield strength is overmatching (80 ksi), while the ultimate tensile strength is greater for the base metal (120 versus 105 ksi). In addition, weld metal elongation and reduction of area values are about half base metal values. It is anticipated that a lower temperature postrolling anneal (less than 2050° F) will produce a yield strength in the base metal approaching 80 ksi.

Charpy V-notch data developed at this laboratory are presented in figures 7 and 8. Both base metal and weldments exhibited excellent toughness. As expected, this stainless steel shows a decrease in toughness with temperature without a sharp transition. From +75° F to -100° F, CVN values are only somewhat lower for GMA weldments compared to base plate. However, at -320° F, the reduction in toughness is 60%-70%. The lowest toughness values from +75° F to -100° F are 60 ft-lb for base metal and 50 ft-lb for GMA weldments.

For purposes of comparison, CVN toughness values obtained for Nitronic 50 are discussed relative to the Navy's currently used structural high strength steel, HY-80. Requirements for the HY-80 are 50 ft-lb at -120° F for base plate (MIL S-16216H) and 50 ft-lb at -60° F for GMA weldments (MIL E-23765/2). Minimum values obtained for Nitronic 50 are approximately 54 ft-lb at -120° F (base metal) and 55 ft-lb at -60° F (GMAW). Shielded metal-arc weldments of Nitronic 50 are also plotted in figure 8. They show at least a 50% reduction in toughness as compared to the GMAW. However, 26 ft-lb at -60° F would still pass the 20 ft-lb requirement for HY-80 SMA weldments (MIL E-22200/1).

The dynamic-tear tests demonstrated excellent toughness as would be expected for an austentic stainless steel. Note the shear lips on the fractures in figure 9. Porosity in the weldment is large and extensive as evidenced by the shiny, spherical areas (see figure 9). However, all DT values for base plate and GMA weldments were above 700 ft-lb at 32 ° F. By comparison, other tests at this laboratory on SMA weldments have produced much lower dynamic-tear values (340-460 ft-lb at 0° F). NRL has recommended a minimum 5/8-inch DT value of 400 ft-lb for HY-80 weld metal at 30° F.

STRESS CORROSION

Cantilever stress-corrosion data for Nitronic 50 base metal and weldments are given in table 4. These tests do not meet ASTM validity criteria for plane strain conditions: i.e., a, B $\geq 2.5\ (K_I/YS)^2$. Stress intensity values (K_{Ii}) versus time-to-failure are plotted in figure 10. Threshold curves normalized to yield strength are presented in figure 11. K_{Iair} values for base metal and weldments are 95.4 and 110.2 ksi $\sqrt{in.}$, respectively; while normalized data, K_{Iair}/YS, are 1.54 $\sqrt{in.}$ (base metal) and 1.38 $\sqrt{in.}$ (weldments). Seawater threshold values of K_{Ii}/YS for 1300 hours are 1.31 $\sqrt{in.}$ (base metal) and 1.26 $\sqrt{in.}$ (weldments). Compared to the step-loaded air values, this is a reduction of only 15% for the base metal and 9% for the weldments.

TABLE 4
STRESS-CORROSION CRACKING RESULTS OF NITRONIC 50
BASE METAL AND WELDMENTS

Specimen No.	Environment	Thickness B in.	Depth W in.	Crack Length a, in.	Total Applied Weight (P_{max}) lb	Total Moment in-lb	Time to Failure hr	K_{Ii} ksi $\sqrt{in.}$	K_{Ii}/YS $\sqrt{in.}$	Corrosion on Fracture Face
					Base Metal					
EKV 001	Air	0.754	1.499	0.772	360.7	10,821.0	-	95.4	1.54	-
EKV 002	SW	0.752	1.497	0.785	334.2	9,693.5	6	87.8	1.42	Yes
EKV 003	SW	0.752	1.498	0.789	313.9	9,102.6	232*	83.1	1.34	Yes
EKV 004	SW	0.753	1.497	0.805	284.7	8,248.5	1290 NF**	78.0	1.26	No
EKV 005	SW	0.753	1.498	0.734	279.4	8,100.0	1290 NF**	73.0	1.18	No
EKV 006	SW	0.754	1.497	0.789	306.4	8,385.4	1295 NF*	81.0	1.31	Yes
					Weldments					
EKV 2[illegible]	Air	0.755	1.500	0.809	410.1	11,892.0	-	110.2	1.38	-
EKV 21[illegible]	SW	0.748	1.499	0.790	385.7	11,185.0	21	102.6	1.28	No
EKV 22	SW	0.755	1.499	0.791	411.3	11,927.6	5 min	108.6	1.36	No
EKV 23[illegible]	SW	0.754	1.499	0.779	300.6	8,716.5	1273 NF**	77.5	0.97	Yes
EKV 24[illegible]	SW	0.754	1.492	0.783	[illegible]	9,740.6	1295 NF**	88.6	1.11	Yes
EKV [illegible]	SW	0.746	1.501	0.813	361.4	10,480.6	1026 NF	101.9	1.26	No

*Crevice corrosion under sealant.
**Severe crevice corrosion under sealant.

NF - No failure.

Figure 12 shows the fracture surfaces of several base metal and weldment SCC specimens broken in air and seawater. Porosity is evident in the weldments (see arrows). Regions of stress corrosion are observed on the fractures of five specimens; e.g., note the dark areas adjacent to the fatigue crack on specimen EKV 003, figure 12.

One problem encountered during the testing of these SCC specimens was crevice corrosion which occurred on many of the specimens under the silastic which sealed the seawater reservoir. For the long-term tests, this crevice may have cathodically protected the notch. The magnitude of the crevice corrosion is further cause for concern. The degree of attack is much greater than that observed on the Nitronic 50 panel in the 30-day Delrin crevice test (see "Crevice Corrosion"). Specimen EKV 004 experienced the greatest level of attack; an area 1/4 x 1/2 inch was corroded to a maximum depth of 70 mils in 53 days.

Since valid plane-strain fracture toughness values (K_{Ic}) are not obtainable with the size of specimens tested in this investigation, a useful comparative measure of toughness is the specimen strength ratio, R_S. (This ratio may be used when results are compared from specimens of the same form and size, and when this size is sufficient that the limit load of the specimen is a consequence of pronounced crack extension prior to plastic instability.) Therefore, relative strength ratios were calculated from the formula given in ASTM E399-74 (modified for cantilever-beam specimens).

$$R_S = 12\ P_{max}\ W/B\ (W-a)^2\ YS\ ,$$

where,

P_{max} = maximum load the specimen could sustain.

B = thickness of specimen.

W = depth of specimen.

a = crack length.

Air tests for base metal and weldments produce relative strength ratios of 0.263 and 0.249, respectively. Threshold seawater values are 0.235 (base metal) and 0.231 (weldments). In both cases, the relative strength ratios (and hence the toughness) for the base metal are greater than for the weldments.

FATIGUE

The results of the fatigue tests for all conditions are plotted in figure 13. In the low-cycle region, smooth base metal tests in air and Severn River water produced similar results, and therefore, one curve was drawn. High-cycle Severn River water data showed only a 30% reduction in fatigue performance compared to the air results: a fatigue strength at 10^8 cycles of 35 versus 50 ksi. Notched air results displayed approximately a 2:1 reduction in low-cycle fatigue strength (theoretical stress concentration factor 2.4). High-cycle, notched Severn River water failures were 50% of smooth Severn River water values.

The GMAW data showed considerable scatter because of porosity in the weldments. All specimens broke in the weld metal. The best performance demonstrated by smooth SRW weldments was no better than that of the notched SRW base metal specimens. A substantial reduction in weld porosity would be necessary to achieve fatigue performance approaching that of the base metal.

Concurrent studies at this Center have shown a marked reduction in GMA weld porosity through a modification of shielding gas composition. Fatigue tests will be performed on modified GMA, as well as GTA and SMA welded plates. Previous Nitronic 50 SMA weldments have shown low weld porosity.

Table 5 compares the high-cycle fatigue behavior of Nitronic 50 to other naval alloys. Only Inconel 625 and Ti-621/0.8 have better fatigue strengths than Nitronic 50 in salt-water. In addition, Nitronic 50 ranks very high when comparing its fatigue strength/yield strength ratio and fatigue strength reduction factor to the other alloys.

TABLE 5
COMPARISON OF HIGH-CYCLE FATIGUE BEHAVIOR
OF VARIOUS NAVAL ALLOYS

Alloy	Yield Strength, ksi (0.2% offset)	Fatigue Strength at 10^8 Cycles, ksi		Fatigue Strength / Yield Strength		Fatigue Strength Reduction Factor*
		Air	Salt Water	Air	Salt Water	
Nitronic 50	62	52	35	0.84	0.56	1.49
304 stainless steel	35	35	15	1.00	0.42	2.33
316 stainless steel	36	39	14	1.08	0.39	2.79
Monel 400	33	35	27	1.06	0.82	1.30
Monel K-500	176	26	18	0.15	0.10	1.44
HY-80	87	44	8	0.51	0.09	5.50
HY-130	157	72	8	0.46	0.05	9.00
Al 5456, H116	33	20	2	0.61	0.06	10.00
Inconel 625	52	57	45	1.10	0.87	1.27
Ti-621/0.8	107	49	49	0.46	0.46	1.00

*Fatigue Strength Reduction Factor = $\frac{\text{Fatigue Strength in Air}}{\text{Fatigue Strength in Seawater}}$.

The smooth low-cycle fatigue behavior of Nitronic 50 in air is compared to the behavior of several other naval alloys in figure 14. As can be seen from the curves, Nitronic 50 outperforms most of the alloys (even HY-80 above 10^4 cycles).

GALVANIC CORROSION

Table 6 presents the results of the galvanic couples tested at Wrightsville Beach. The coupled and freely corroding corrosion rates are only valid for comparison purposes in these 30-day tests and should not be considered as accurate yearly values.

TABLE 6

RESULTS OF POLARIZATION TESTS OF NITRONIC 50 GALVANICALLY COUPLED WITH VARIOUS ALLOYS

SW Flow: 3 ft/sec — Avg SW pH: 7.9
Reference Cell: Ag/AgCl — Avg SW Salinity: 34.5 ppt
Avg SW Temp: 77° F — Days in Test: 30

Couple No.	Alloy	Corrosion Rate, mpy		Nitronic 50 Corrosion Rate, mpy, (mils)[1]	Galvanic Current, ma		Mixed Potential (Range, mv)
		Coupled	Freely Corroding		Avg	Max	
1	HY-80	68.6	24.3	Nil	2.0	3.0	-600 to -640
2	HY-130	73.5	23.9	Nil	2.2	3.6	-585 to -625
3	HY-180	74.6	31.6	Nil	2.0	3.4	-500 to -570
4	5086 Al	65.7[2]	5.5	Nil	2.1	3.8	-720 to -750
5	90-10 Cu-Ni	62.3	1.8	Nil	1.3	3.0	-80 to -170
6	Ni-Al Bronze	36.9	2.8	Nil	1.1	2.2	-20 to -110
7	Cast 70-30 Cu-Ni	37.9	1.3	Nil	1.1	2.7	-65 to -145
8	CA 715	15.2	1.9	Nil	0.39	0.9	-15 to -170
9	CA 719	19.4	0.3	Nil	0.42	0.6	-40 to -65
10	304 Stainless Steel	15.5[2]	2.2[3]	Nil, (7)	0.25	0.6	-20 to -100
11	17-4 PH	38.5[2]	16.9[2]	Nil, (4)	0.67	0.9	-70 to -200
12	Monel 400	2.7[3]	0.1	Nil, (4)	Nil	0.1	-30 to -50
13	Inconel 625	Nil	Nil	Nil, (12)	Nil	±0.1	+190 to -90
14	Ti-621/0.8	1.8	Nil	Nil, (11)	Nil	±0.1	+115 to -105
15[4]	Nitronic 50	-	0.6(14)[1]	1.7, (26)	-	-	+50 to -70[5]

[1] Crevice corrosion (maximum pit depth).
[2] Severe crevice attack.
[3] Pitting attack.
[4] Freely corroding specimens.
[5] Freely corroding potential.

None of the Nitronic 50 samples evidenced any corrosion on their exposed faces even when coupled to Inconel 625 and titanium. Some crevice corrosion was observed on five of the Nitronic 50 couples and more severely on the freely corroding samples. This attack, in the form of localized pits, occurred on the backs and edges of specimens as a result of seawater leakage under the masking coating.

Corrosion rates were nil on the Nitronic 50 coupled samples; even on those that had some crevice attack, the pits were not broad and hence the weight loss was negligble. In contrast, the other stainless steels (304 and 17-4 PH) displayed substantial attack. The HY steels, the copper-base alloys, and 5086 aluminum all showed large weight losses. Nitronic 50 behaved as the cathode in most tests (couples 1-11) and, as a result, accelerated the corrosion rates of the coupled alloys (see table 3).

In the case of the Monel sample, massive but shallow pitting attack was observed. Furthermore, the weight loss of this panel was very low as was the measured galvanic current. It appears, therefore, that coupling Nitronic 50 to Monel 400 does not markedly accelerate the corrosion rate of Monel.

As expected, the titanium and the Inconel couples showed no signs of corrosion. (A weight loss of 1 8 mpy was measured on the titanium sample, but no change in appearance was noted.) The galvanic current measured between these noble alloys and Nitronic 50 was essentially zero. It is interesting to note that there was less attack observed on these coupled Nitronic 50 panels than the freely corroding Nitronic specimens.

CREVICE CORROSION

Prior to the Delrin multiple-crevice screening studies, four Nitronic 50 general and six crevice-corrosion panels were exposed in low velocity seawater (2 ft/sec) for varying periods of time (6, 12, 24 months). The surface and edges of each specimen were machined and ground. Each crevice panel measured 3 x 12 inches and was fitted with one 1 x 1 inch nylon and one Nitronic 50 washer bolted to opposite faces. The results of the exposures are presented in table 7. No general pitting attack occurred even for the 24-month tests. Crevice corrosion was slight except for panel 8. It is interesting to note that the 24-month exposures displayed less crevice attack than the 12-month tests indicating the statistical nature of the phenomenon.

TABLE 7
NITRONIC 50 GENERAL- AND CREVICE-CORROSION EXPOSURES

Panel No.	Duration of Exposure months	Remarks
		General-Corrosion Panels, 3 1/2 x 6 1/2 inches
1	12	No pitting
2	12	No pitting
3	24	No pitting
4	24	Four shallow pits less than 1 mil deep,* three 1/32-inch diameter and one 1/8-inch diameter
		Crevice-Corrosion Panels, 3 x 12 inches with 1- x 1-inch Nitronic 50 Washers
5	6	Extremely shallow uniform attack under crevice and on washer (<1 mil), has etched appearance.
6	6	No attack on panel or washer
7	12	Shallow uniform under crevice (1-4 mils deep)
8	12	Panel: crevice corrosion; 25 mils maximum depth on one side of panel, 35 mils on other side Washer: maximum 30 mils deep
9	24	Small lightly "etched" area under crevice
10	24	Similar to panel 9

*Pits occurred under barnacle attachment.

Tables 8 and 9 present the results of the multiple-crevice screening tests. The test conditions, weight loss, and depth of attack are listed in table 8. Unfortunately, a large number of specimens suffered edge attack, in many cases, in preference to attack under the crevice assembly. This was attributed to edge roughness and prevented a statistical evaluation of the multiple-

crevice test. In lieu of this statistical evaluation, an appraisal of crevice, edge, and bold surface attack was made, and five categories were established (see table 9). Pit depth, number of corroding sites, and weight loss were all considered in the determination of the severity of attack.

TABLE 8

RESULTS OF CREVICE-CORROSION TESTS OF VARIOUS STAINLESS STEEL ALLOYS

Avg SW Tem;: 79.3° F
Avg SW pH: 8.0
No. of Crevices per Panel: 40

Avg SW Salinity: 34.4 ppt
Days in Test: 30
Bold/Shielded Surface Area Ratio: 300/1

Alloy	Weight Loss, grams	No. of Corroding Crevices	Max Depth of Attack mils			Remarks (Nature of Attack)
			Crevice	Edge	Bold	
304	2.66	0	0	185	0	Edge (S)
304L	7.61	40	64	330	0	Edge (S), crevice (S)
316	2.81	0	0	154	0	Edge (S)
316L	2.97	21	20	160	0	Edge (S), crevice (M)
310	2.91	33	25	140	0	Edge (S), crevice (M)
309	3.07	15	11	175	0	Edge (S), crevice (L)
321	2.09	31	52	325	0	Edge (S), crevice (S)
330	3.82	40	17	150	0	Edge (S), crevice (L)
347	2.05	16	32	215	0	Edge (S), crevice (M)
317	0.96	0	0	70	0	Edge (M)
Nitronic 40 (21-6-9)	0.50	1	5	194	0	Edge (S), crevice (L)
Nitronic 50 (22-13-5)	0.12	16	16	0	0	Crevice (L), numerous shallow [illegible]
17-4 PH	2.57	1	29	240	0	Edge (S), crevice (M)
17-7 PH	1.24	6	28	120	0	Edge (S), crevice (M)
15-5 PH	2.73	21	53	334	0	Edge (S), crevice (S)
PH 15-7 Mo	0.80	2	7	165	0	Edge (S), crevice (L)
Nitronic 33 (18-3 Mn)	1.76	16	15	75	0	Edge (S), crevice (L)
Uniloy 26-1	Nil	0	0	0	0	Nil
Crucible 26-1	Nil	0	0	0	0	Nil
29 Cr-4 Mo	Nil	0	0	<60	0	Edge (L), several small edge pits
AFC-77	0.03	0	0	31	0	Edge (M), one large pitted area
AM-355	0.25	0	0	158	0	Edge (M), large number of pits
AM-363	4.40	30	>64 (P)	0	>64 (P)	Edge (S), bold (S)
AM-367	1.94	30	55	0	>84 (P)	Edge (S), bold (S)
A-286	0.77	11	>64 (P)	0	>64 (P)	Crevice (S), bold (S)
AL-6X	Nil	0	0	0	0	Nil
Tenelon	0.97	6	24	105	>70 (P)	Edge (S), crevice (S), bold (S)
19-2	Nil	7	9	0	>20	Crevice (L), bold (L), one bold pit
Carpenter 20Cb-3	0.12	2	83	0	0	Crevice (M), one deep crevice
Custom 450*	0.19	6	96	0	0	Crevice (S)
Custom 455*	2.06	29	>80 (P)	>80 (P)	>80 (P)	Edge (S), crevice (S), bold (S)
18-8-2	0.45	18	39	0	50	Crevice (M), bold (M), one deep pit
304*	0.80	26	46	>50	>60 (P)	Edge (S), crevice (S), bold (S)
316*	0.71	6	14	>50	>60 (P)	Edge (S), crevice (L), bold (S)
304*	0.53	14	>60 (P)	0	>60 (P)	Crevice (S), bold (S)

*Undersize panel: bold/shielded area ratio 150/1.

(P) - Specimen perforated
(S) - Severe
(L) - Light
(M) - Moderate

TABLE 9

CREVICE-CORROSION SCREENING STUDY
ALLOY COMPOSITION AND GROUPING

Alloy	Nominal Chemical Composition, wt %										Typical YS, ksi
	C*	Cr	Ni	Mn	Mo	Cb + Ta	N	Ti	Cu	Misc	Fe	
						I. Severe Attack						
304	0.08	19.0	9.0	2.0*	-	-	-	-	-	-	Bal	35
304L	0.03	19.0	9.5	2.0*	-	-	-	-	-	-		33
316	0.08	17.5	13.0	2.0*	2.5	-	-	-	-	-		36
316L	0.03	18.0	13.0	2.0*	2.5	-	-	-	-	-		34
310	0.25	25.0	20.0	2.0*	-	-	-	-	-	-		45
309	0.20	23.0	13.0	2.0*	-	-	-	-	-	-		40
321	0.08	18.0	10.0	2.0*	-	-	-	0.4*	-	-		30
347	0.08	18.0	11.0	2.0*	-	0.8 minimum	-	-	-	-		35
330	0.08	18.5	35.5	2.0*	-	-	-	-	-	-		45
Nitronic 33	0.08	18.0	3.0	13.0	-	-	0.2-0.4	-	-	-		68
Nitronic 40	0.08	20.5	6.5	9.0	-	-	0.15-0.4	-	-	-		68
17-4 PH**	0.07	16.5	4.0	1.0*	-	0.3	-	-	4.0	-		95-185
17-7 PH**	0.09	17.0	7.0	1.0*	-	-	-	-	-	1.2Al		40-185
15-5 PH**	0.04	15.0	4.5	1.0*	-	0.3	-	-	3.3	-		85-185
15-7 PH Mo**	0.09	15.0	7.0	1.0*	2.5	-	-	-	-	1.0Al		55-210
AM-363**	0.04	11.7	4.7	0.3*	-	-	-	0.6	-	-		118
AM-362**	0.03	14.0	6.7	0.3*	-	-	-	0.8	-	-		108-210
A286	0.05	15.0	26.0	1.4	1.2	-	-	2.2	-	0.2Al; 0.3V		100
Tenelon	0.10	18.5	0.2	15.0	-	-	0.5	-	-	-		70
Custom 455**	0.03	11.5	8.5	0.5	-	0.3 minimum	-	1.2	2.25	-		125-245
						II. Moderate/Severe Attack						
Custom 450**	0.05	15.0	6.5	0.5	0.8	0.4 minimum	-	-	1.5	-	Bal	95-190
317	0.08	19.0	13.5	2.0*	3.5	-	-	-	-	-		40
18-8-2	0.06	18.0	18.0	1.5	-	-	-	-	-	2.0Si		36
20Cb-3	0.06	20.0	34.0	2.0*	2.5	0.5 minimum	-	-	3.5	-		40-55
AM-355**	0.15	15.5	4.3	1.0	2.8	-	0.12	-	-	-		60-156
						III. Moderate/Light Attack						
AFC-77	0.15	14.2	-	-	4.6	-	-	-	-	0.3V; 13 Co	Bal	81-233
29Cr-4Mo**	0.01	29.0	0.1	0.1	4.0	-	-	-	-	-	Bal	60
						IV. Light Attack						
Nitronic 50	0.06	21.5	12.0	4.5	2.2	0.2	0.2	-	-	-	Bal	60
JS-700	0.03	21.0	25.0	1.7	4.5	0.3	-	-	-	-	Bal	40
						V. No Attack						
AL-6X	0.04	20.0	24.0	1.5	6.5	-	-	-	-	-	Bal	44
26-1**	0.02	26.0	0.25	0.3	1.0	-	-	0.4	-	-	Bal	52

*Maximum.
**Magnetic alloy.

Twenty alloys fall into the "severe" category. These include the 300 series and most of the age-hardenable grades of stainless steel. Also, the high manganese alloys (Nitronic 33, Nitronic 40, Tenelcn) performed very poorly. Class II alloys exhibited a somewhat less intense attack than those in class I. The "moderate-to-light" group (class III) showed a definite improvement in crevice corrosion behavior. Both alloys in this category, AFC-77 and 29Cr-4Mo, had essentially no weight loss, but pit depths for each were significant. Nitronic 50 and JS-700 constitute the "light attack" group (class IV). These stainless

steels had almost no weight loss and very shallow crevice corrosion (20 mils maximum). Only two alloys, AL-6X and 26-1 (Uniloy and Crucible) were unaffected by the 30-day seawater exposure (class V).

For most grades of stainless, it appears that a high chromium content coupled with sufficient amounts of molybdenum are necessary to ensure crevice-corrosion resistance. One anomaly appears in the results: alloy 29Cr-4Mo, with greater alloy content than alloy 26-1, showed some edge pitting attack while both the 26-1 panels were unaffected. One explanation may be local specimen test conditions such as edge roughness. Also, it must be remembered that these tests are statistical and were only run for 30 days (see discussion of Westinghouse results). It would be desirable to rerun tests on the alloys in classes III to V to verify these results.

Comparison of these exposures with seawater crevice-corrosion tests of longer duration (2 to 4 months) performed by Westinghouse Electric's Oceanic Division indicate some variance. Agreement was found with grades 304 and 316, which performed poorly, and alloy AL-6X, which showed no attack. In contrast, 316L stainless performed much better in the Westinghouse study. Our 29Cr-4Mo panel showed some edge pitting while our 26-1 samples were unaffected. Just the opposite was reported in the other study. In all cases, the Nitronic 50 panels displayed crevice attack, more deeply in the Westinghouse study because of the longer exposure time. One grade of stainless, type 216, (unavailable for our tests) demonstrated better corrosion resistance than Nitronic 50 in the Westinghouse tests. This alloy is also nitrogen strengthened (20Cr-8Mn-6Ni-2.5Mo-0.3N) with about the same yield strength as Nitronic 50. This behavior should be verified since type 216 has a leaner alloy composition than Nitronic 50.

MAGNETIC PERMEABILITY

The magnetic permeability for Nitronic 50 base plate is 1.004 at 50, 100 and 200 oersteds (Armco Steel Data). Because of a small amount of ferrite present in the weld metal, slightly higher permeabilities were measured for the weldments: 2.140 (50 Oe), 2.165 (100 Oe), and 2.027 (200 Oe). A ferrite number of 8 was obtained from Magne-gage measurements.

SUMMARY

- Nitronic 50 base metal and GMA weldments have moderate strength and elongation. Weld metal yield strength is overmatching, while the ultimate tensile strength is greater for the base plate.

- By employing a lower temperature postrolling anneal, an increased base metal yield strength should be realized.

- Dynamic-tear and Charpy V-notch toughness values exceed the minimum requirements established for HY-80 steel.

- Threshold seawater stress-corrosion values compared against a step-loaded air value show a reduction of only 15% for base metal and 9% for GMA weldments.

- The fatigue behavior of Nitronic 50 base metal is very good in both the high- and low-cycle range. GMA weldment performance is poor and is attributed to excessive weld porosity. The fatigue behavior of GMA, GTA, and SMA weldments with lower porosity levels is currently being evaluated.

- The seawater-corrosion behavior of Nitronic 50 is not adversely affected when coupled to common machinery alloys or with more noble materials such as titanium and Inconel 625.

- Nitronic 50 is cathodic when coupled to HY steels, copper-base alloys, aluminum, and most other stainless steels and accelerates their corrosion rates.

- Nitronic 50 does not display general pitting corrosion in seawater. However, as is the case for almost all stainless steels, it is susceptible to crevice corrosion. Incubation periods vary greatly. In the 30-day crevice test, this alloy displayed only light attack as compared to the extensive attack experienced by 304 and 316 stainless steels.

- Only one austenitic grade (AL-6X) and one ferritic alloy (26Cr-1Mo) showed no attack in the 30-day crevice exposures.

CONCLUSIONS

Nitronic 50 stainless steel is a promising nonmagnetic alloy for use in the marine environment. This alloy displays good strength, toughness, and fatigue behavior. Its seawater-corrosion resistance is superior to the standard 300 series stainless steels, but it is not immune to local attack.

TECHNICAL REFERENCES

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2 - Gross, M. R., "Low-Cycle Fatigue of Materials for Submarine Construction," Naval Engineers Journal, Vol. 75, No. 5, pp. 783-797 (Oct 1963)

3 - Anderson, D. B., "Statistical Aspects of Crevice Corrosion in Sea Water," TL-265-T-OP, Presented at ASTM-ASM Symposium on Pitting Corrosion, Detroit, Michigan (23 Oct 1974)

4 - DeLong, W. T., "Calibration Procedure for Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal," Welding Journal, Research Supplement, pp. 69-S to 72-S (July 1973)

Longitudinal Section

Specimen EXV 299, 100X

Etch: Electrolytic
10% Chromic Acid, 250X

Transverse Section

Specimen EXV 299, 100X

Etch: Electrolytic
10% Chromic Acid, 250X

Figure 1
Microstructures of One-Inch-Thick Nitronic 50 Plate
(As-Rolled and Annealed Condition)

Etch: Electrolytic, 10% Chromic Acid, 75X

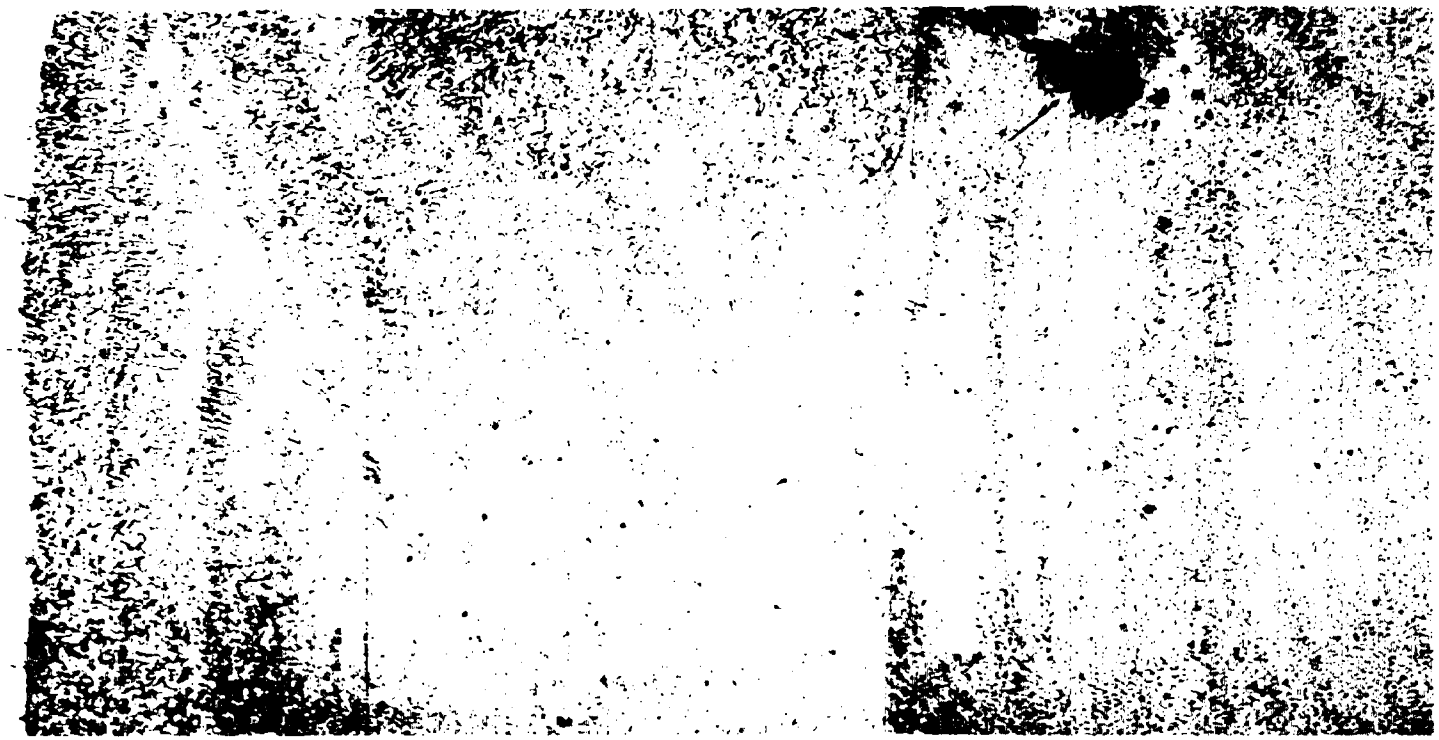


Figure 2
Montage of Nitronic 50 GMA Weldment

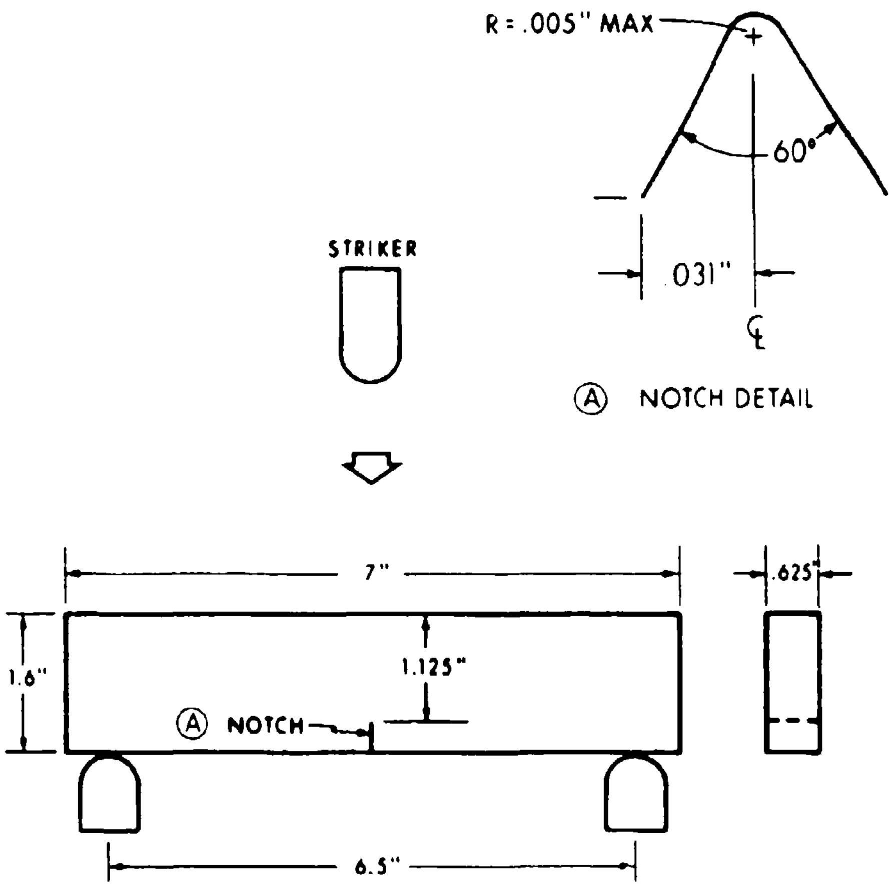


Figure 3
Dynamic Tear Test Specimen

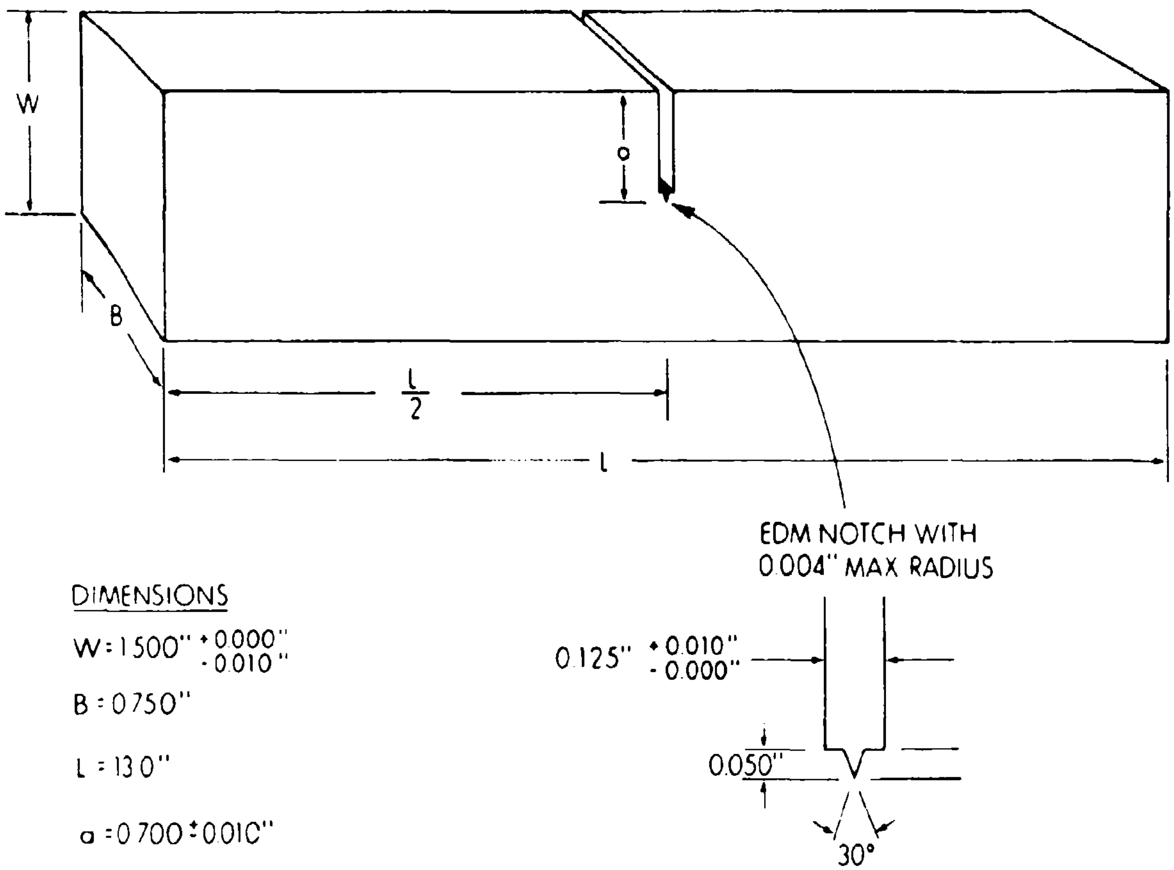


Figure 4
Notched Cantilever-Beam Stress-Corrosion Specimen

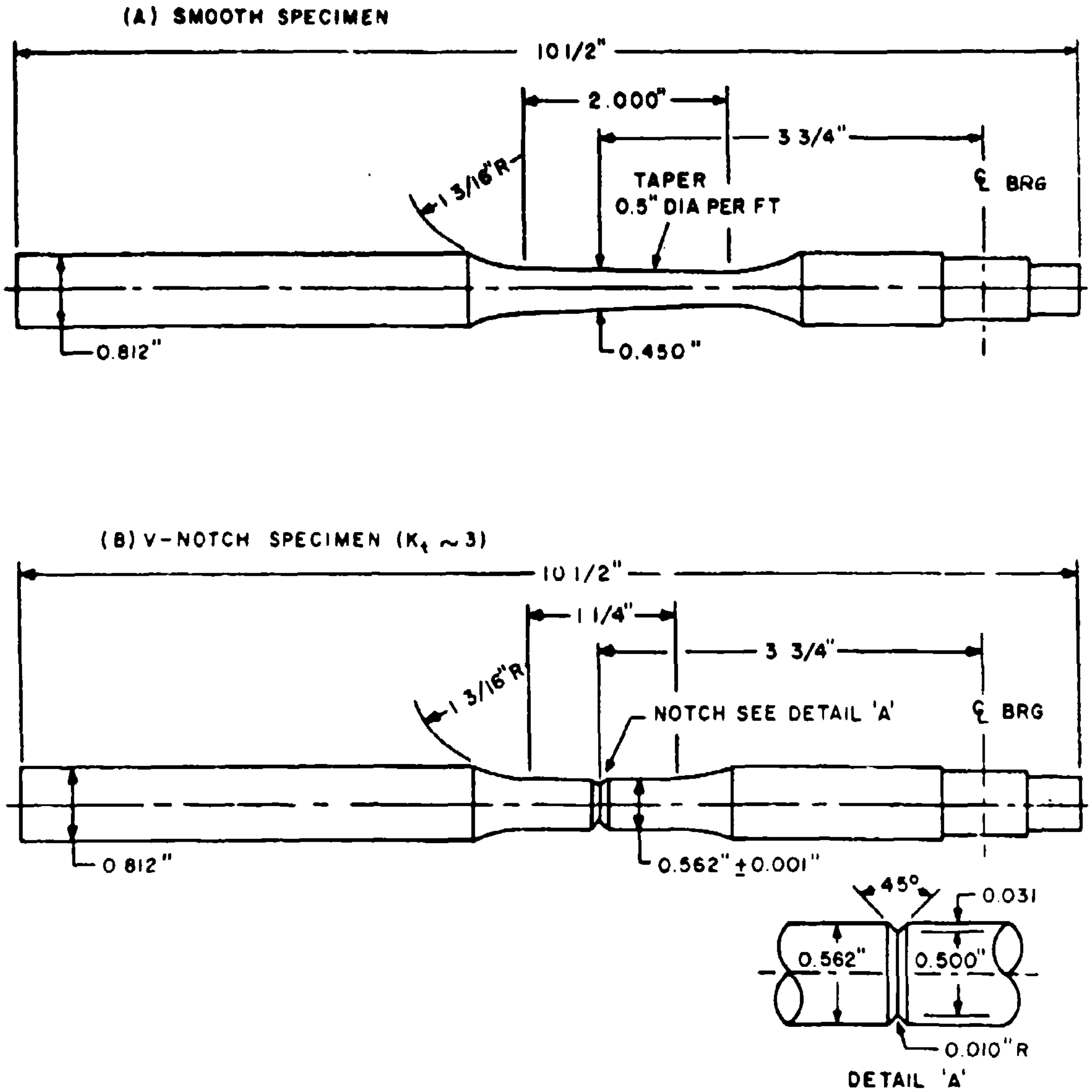
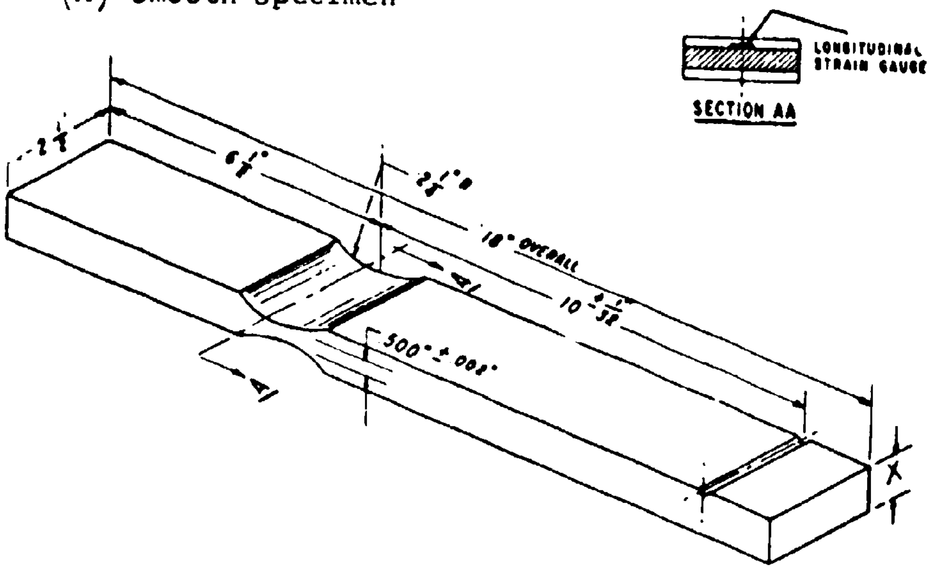


Figure 5
High-Cycle Fatigue Specimens

(A) Smooth Specimen



(B) V-Notch Specimen ($K_t \sim 2.4$)

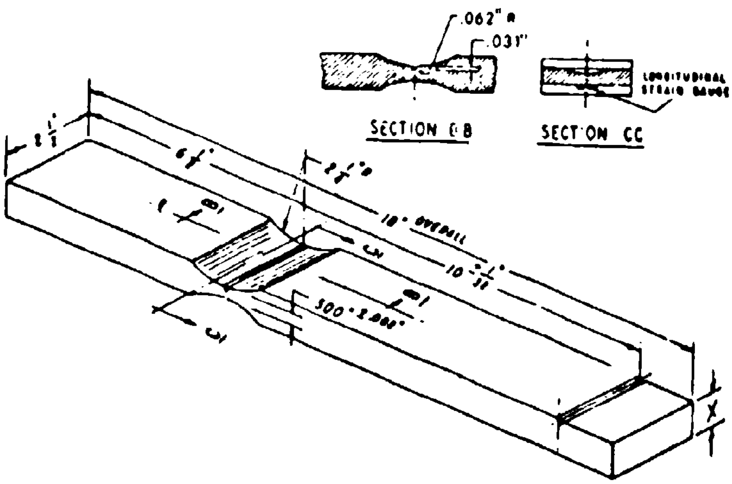


Figure 6
Low-Cycle Fatigue Specimens

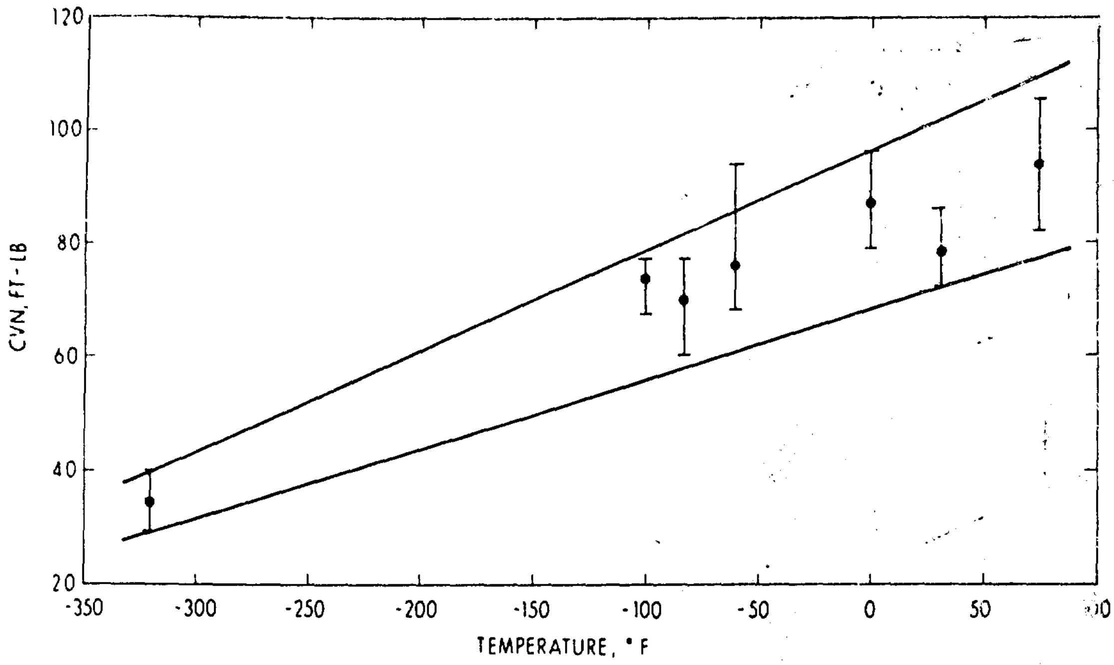


Figure 7 - Charpy V-Notch Impact Toughness
Versus Temperature for Nitronic 50 Base Plate

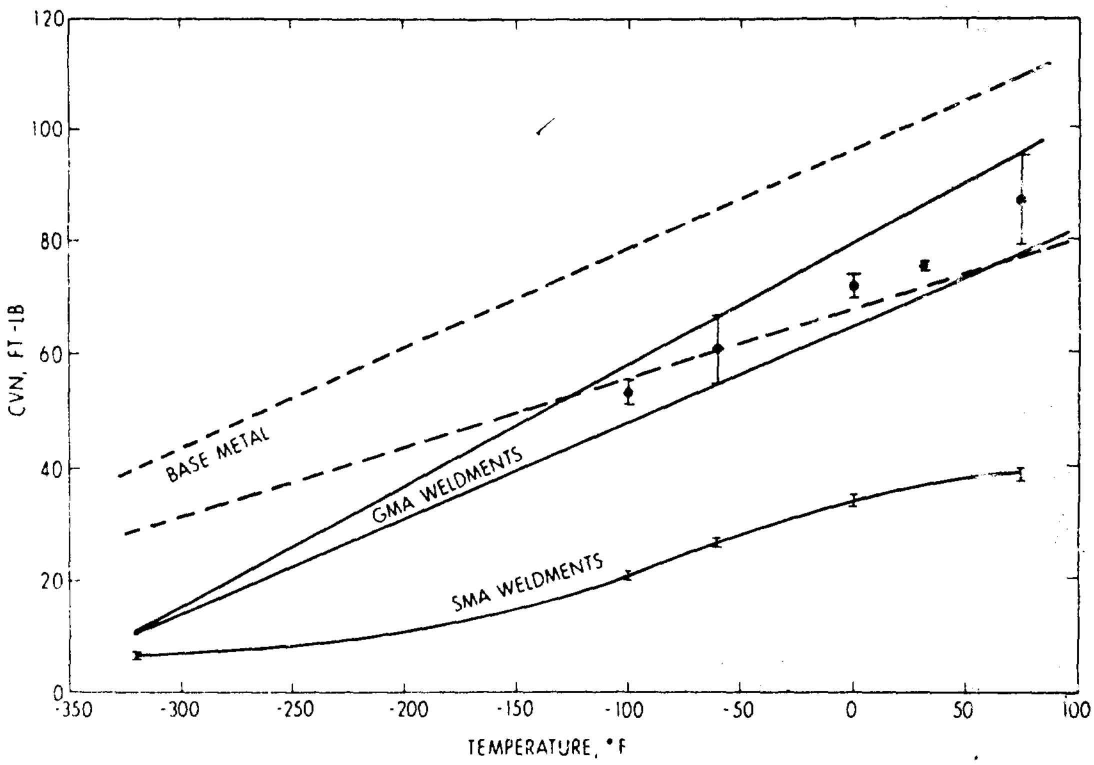
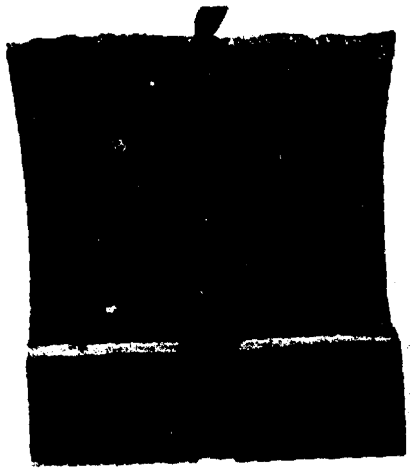


Figure 8 - Charpy V-Notch Toughness
Versus Temperature for Nitronic 50 Weldments



Base Metal - 700 ft-lbs
at 32° F

Specimen EXV 421

Weldment - 770 ft-lbs
at 32° F

Specimen EXV 195

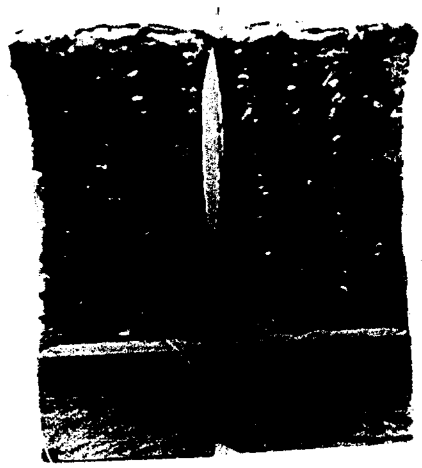


Figure 9
Fracture Surfaces of Failed 5/8-Inch
Dynamic Tear Specimens, 1.4X

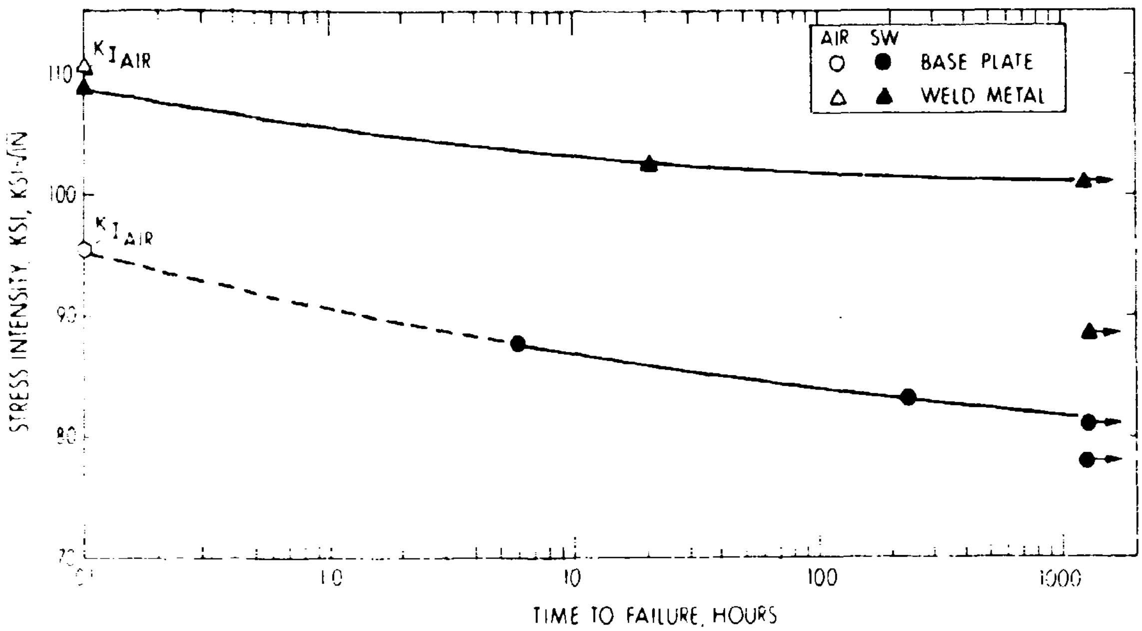


Figure 10
Stress Intensity Threshold Curves in Seawater
for Nitronic 50 Base Metal and Weldments

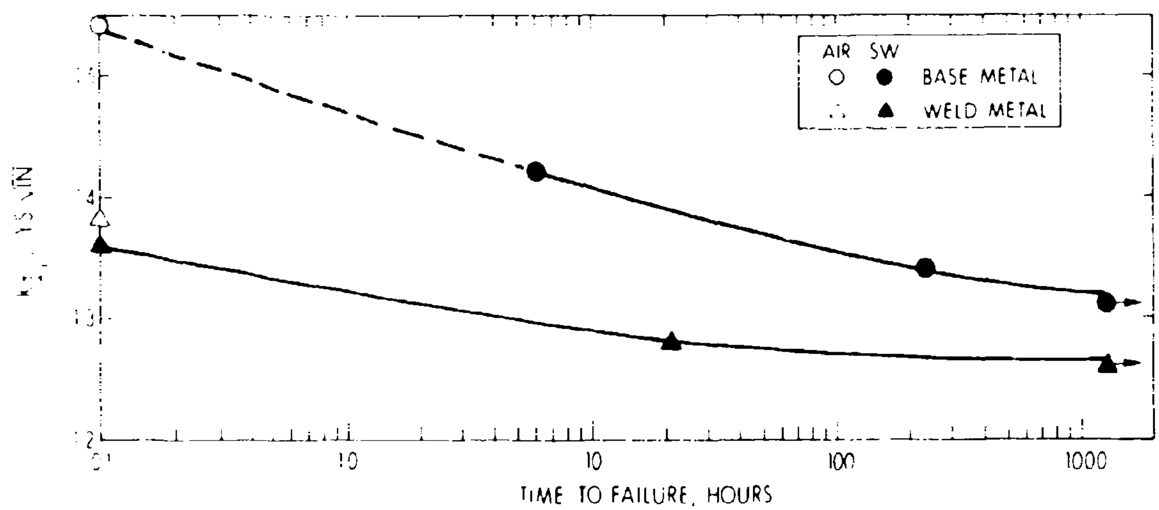
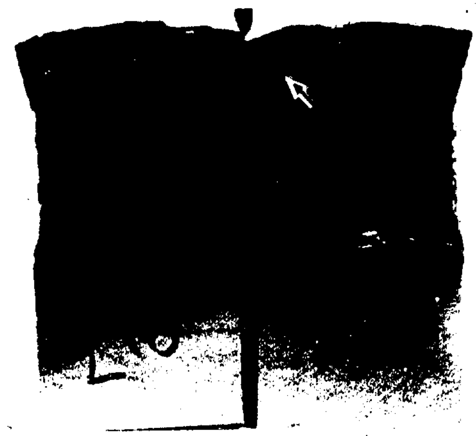


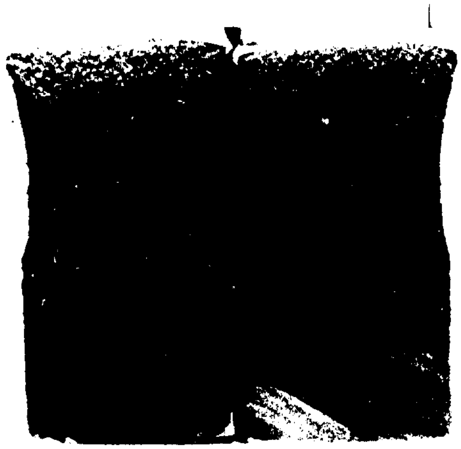
Figure 11
Seawater Threshold Curves for Nitronic 50
Base Metal and Weldments

Air, Weldment
EXV 200
Step-Loaded to Failure

Seawater, Weldment
EXV 210
Failure: 21 hours



Air, Base Metal
EKV 001
Step-Loaded to Failure



Seawater, Base Metal
EKV 003
Failure: 232 hours

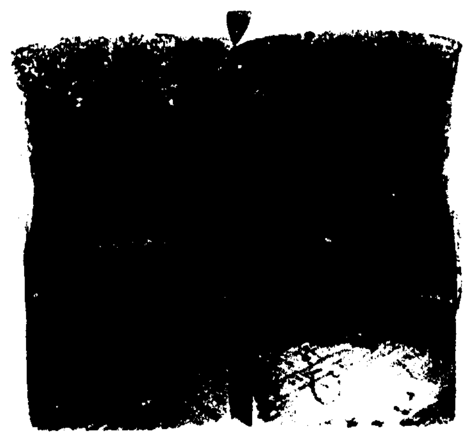


Figure 12
Fracture Surfaces of Failed Cantilever-Beam
Stress-Corrosion Specimens, 1.4X

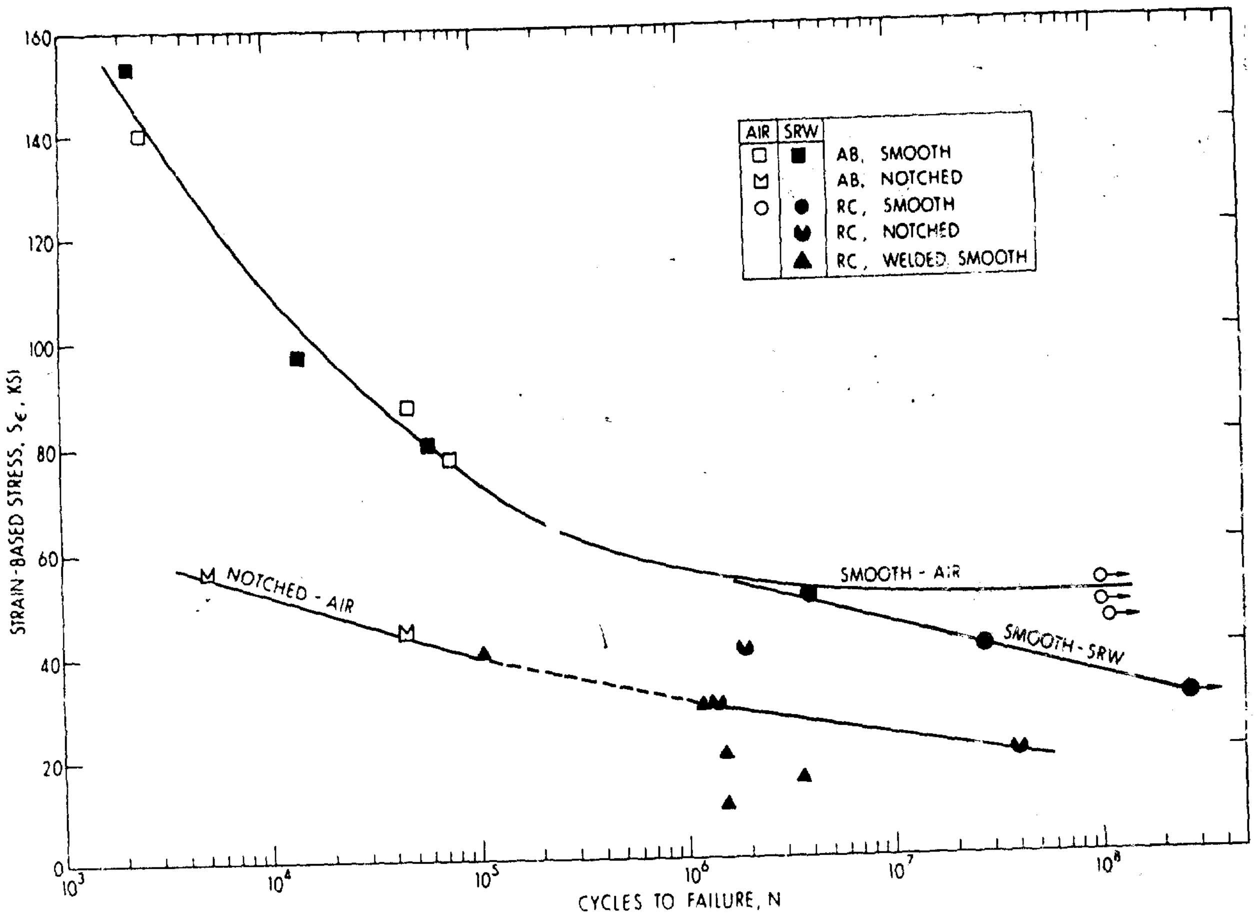


Figure 13
Fatigue Properties for Nitronic 50 Plate

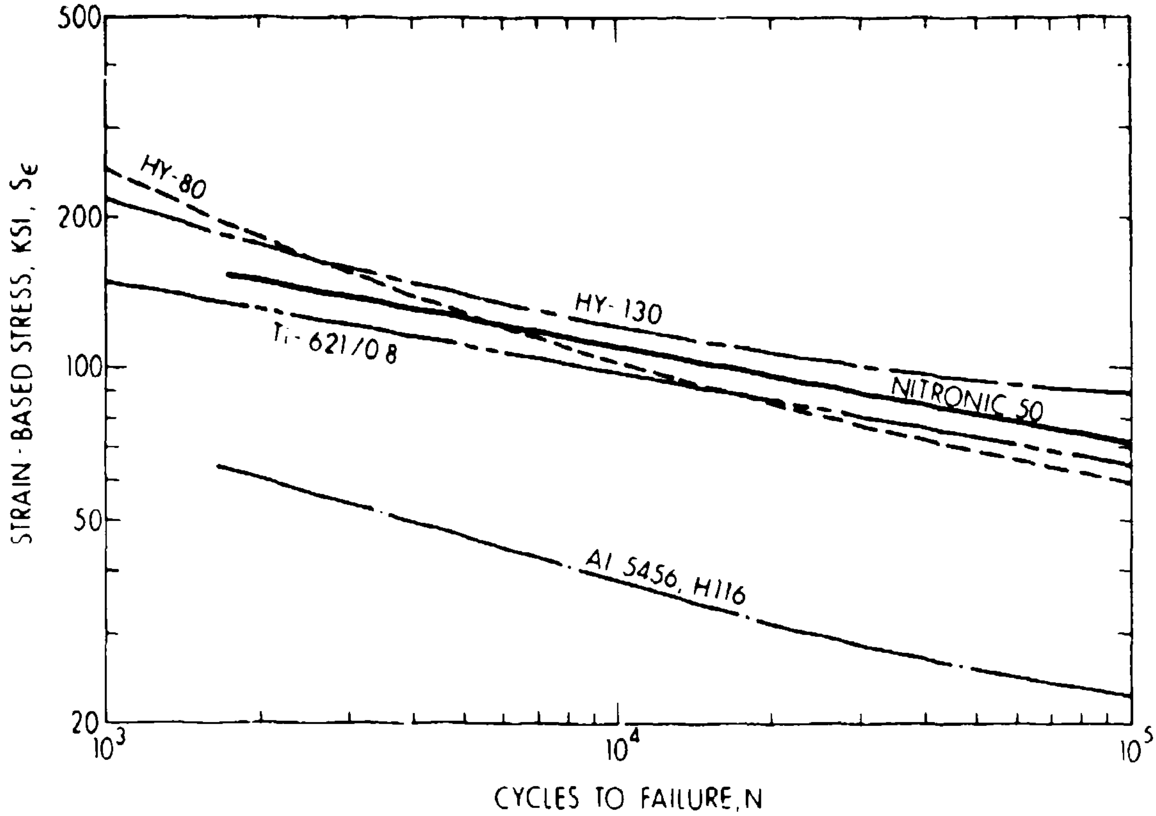


Figure 14
Low-Cycle Fatigue Behavior of Various
Naval Alloys (Smooth Air Tests)

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